Sequence Stratigraphic Modeling of Pennsylvanian-Age Cyclothems

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ABSTRACT

Computer simulations of Pennsylvanian strata in an Appalachian-type foreland basin, an Illinois-type cratonic basin, and a Forest City-type platform basin were generated in an effort to determine whether a unifying sea level pattern across North America could reproduce the stratigraphy of three different, but coeval, basins. One sea level curve was used to drive sedimentary deposition (in combination with other sedimentary and tectonic factors). One sea level curve can be successfully applied to produce stratigraphic results similar to the actual rock records of the Pennsylvanian in the Appalachian, Illinois, and Forest City basins. The resulting stratigraphic cyclicity, stratigraphic thicknesses, lithologies, and proportions of sand to shale to carbonate were compared to actual measurements for each basin, and a close match (with same thickness differences) exists. Problems with modeled thicknesses for the Morrowan/Atokan and Missourian stages compared to actual rock thicknesses may be due to overestimation and underestimation, respectively, of time represented by the sedimentary units.

INTRODUCTION

This paper describes results of a computer modeling study of Pennsylvanian age sequence-stratigraphic units from three coeval (simultaneously deposited) basins (Figure 1) on the ancestral North American continent. A sequence, the basic unit of sequence stratigraphy, is a succession of genetically related rocks that are traceable laterally over large areas, and are bounded by unconformities or their lateral conformities (Van Wagoner et al., 1987, 1988). Sequence stratigraphy is the study of unconformity-bounded stratigraphic units (Vail, 1977; Van Wagoner et al., 1987). Unconformities are physical breaks in the rock record, and are commonly related to changes in relative sea level. Such breaks or surfaces make possible the correlation of sedimentary rocks on a widespread, sometimes worldwide, basis. For the purposes of this study, the major sequences for the Pennsylvanian Period (the time interval 320 to 286 million years ago) are taken to be, in ascending order, the Morrowan/Atokan, Desmoinesian, Missourian, and Virgilian stages (Figure 2).

Cyclothems (Figure 3), which are distinctive, usually coal-bearing, cyclic successions of sedimentary rock, are classic examples of unconformity-bounded depositional sequences. The term cyclothem was first applied to cyclic strata of Pennsylvanian age in the North American Midcontinent (Weller, 1930; Moore, 1931), but subsequently the term has been applied more widely to the stratigraphic record (e.g., Weller, 1964; Van Wagoner et al., 1987, 1988; Watney et al., 1989). Cyclothems are thought to have formed because of the interaction of sea level rises and falls with sedimentary processes (Heckel, 1977, 1979, 1985; Klein and Willard, 1989; Ross, 1991; Klein and Kupperman, 1992; Vail, 1992), and are an important proxy for global change. Because much of the rock record seems to be cyclic, cyclothems, which are outstanding examples of such cyclicity, lend insight into the geologic mechanisms that govern sedimentary processes.

The purpose of this paper is to report on computer modeling of Pennsylvanian cyclothemic deposits in three distinctly different types of basins (Figure 1) on the ancestral North American continent (Figure 4), Laurasia (or Laurussia). The intent of the study was to apply one eustatic (worldwide) sea level curve to three basins, each of which had different subsidence curves, tectonic histories, and other sedimentary variables, to develop an understanding of how major sequence boundaries should be developed basin wide under different stratigraphic regimes if changes in eustatic sea level are the primary forcing mechanism of cyclothem development. Comparisons were made among the development of a foreland basin (the Appalachian basin; Figure 5), an intracratonic basin (the Illinois basin; Figure 6), and a platform basin (the Forest City basin; Figure 7). Basin reconstructions were modeled using SEDPAK version 3.2 software, a computer-generated, basin-fill simulation program (Kendall and Lerche, 1989; Kendall et al., 1989, 1991; Cannon and Kendall 1994). This is perhaps the first attempt to use SEDPAK as a predictive tool to model the stratigraphy of different, but coeval, basins. Using SEDPAK to model sedimentary accumulation across these three basins suggests that sea level changes can force unconformity-bounded sedimentary packages of cyclothemic type and scale to be deposited.

METHODOLOGY

Geologic time units. The geologic time scale used was modified from Harland et al. (1982). The upper and lower boundaries of the Pennsylvanian Period are taken to be 286 Ma and 320 Ma respectively. Time boundaries separating the inferred sequence boundaries (Figure 2) were determined based on the Harland et al. (1982) correlations. As used in this study, these are the geologic intervals and their durations: Morrowan/Atokan Stages, 320 to 301 Ma (duration = 19 my); Desmoinesian Stage, 301 to 295 Ma (duration = 6 my); Missourian Stage, 295 to 292 Ma (duration = 3 my); and Virgilian Stage, 292 to 286 Ma (duration = 6 my).

Sedimentary accumulation. Stratigraphic thickness (present-day values) in the three basins were determined from measured stratigraphic thicknesses available in the literature (Figures 5-7). The minimum and maximum amounts of subsidence during the Pennsylvanian and the thickness of delithified sediments were calculated using decem2, a delithification (or backstripping) software program (Kominz and Bond, 1986, Tables 1-3). From the subsidence values the initial basin geometries were estimated and the subsidence rates were calculated. From the delithified sediment thicknesses, rates of sediment influx were calculated.

The original stratigraphic data entered into decem2 consisted of present stratigraphic thicknesses, lithologies, and proportions of shale to sandstone to carbonate from two or three selected locations in each basin (Figures 5-7).

Basin modeling. Basin reconstructions (Figures 8-10) were generated using SEDPAK version 3.2, a computer generated, two-dimensional, basin-fill simulation program. SEDPAK models the geometry of a basin (distance in kilometers and depth in meters) resulting from the interaction between sea level variation (time in millions of years and depth in meters), sediment accumulation (square kilometers per thousand years), and tectonic subsidence (meters per thousand years). The input data used for SEDPAK consisted of a constant sea level curve (Ross and Ross, 1987, Figure 11), superimposed on Milankovitch-type orbital parameters (Figures 12-14), subsidence rates, and sediment accumulation. Subsidence rates and sediment accumulation rates were calculated from values obtained using the decem2 program and adjusted, to within minimum and maximum parameters, to fit the sea level curve. SEDPAK interpreted the data and distributed sediment across the basin in time sequences of 250,000 years. The amount of sediment deposited during each time interval is represented by a layer of shale, sand, and carbonate, with shale marking the bottom of the sequence and carbonate marking the top. On each of the models (Figures 8-10), the major sequences boundaries are indicated by numbers representing part of their interval of development in millions of years ago. Numbers are: 301.149, representing the

Morrowan-Atokan/Desmoinesian boundary; 295.089 representing the Desmoinesian/Missourian boundary; 292.059, representing the Missourian/Virgilian boundary; and 286.000, representing the Virgilian/Devonian boundary. The dots represent paleoshorelines.

Sea level. Interpretation of unconformity-bounded sedimentary packages provides a means of modeling sea level rises and falls. Identification of a unifying sea level pattern across North America is expected to be used for refining current sea level patterns for the entire world (e.g., Vail, 1977). With this in mind, the same eustatic sea level curve was used for each of the three basins (Figure 11), acting as the primary forcing mechanism of sedimentary deposition. The eustatic sea level curve was superimposed on Milankovitch-type orbital parameters (Figures 12-14). Orbital parameters were designed to increase in amplitude from east to west to allow for the increasing effects from glacio-eustatic processes in cratonic settings (see Watney et al., 1989; Heckel, 1985, 1986; Klein and Willard, 1989; Bunker et al, 1988; Klein and Kupperman, 1992). The resulting stratigraphic thicknesses, lithologies, and proportions of shale to sand to carbonate (Figures 5-7; Table 4) were compared to the actual rock record from each basin to gauge the reliability of the Ross and Ross (1987) sea level curve and the placement of chronostratigraphic boundaries (compare Figures 5-7 with Figures 15-17) used to define the age and duration of each sequence boundary.

Field Studies. Field trips were taken into selected areas of the Appalachian, Illinois, and Forest City basins to observe first-hand Pennsylvanian deposits, as outcrops permitted. Field study helped me better understand the scale of the geologic deposits, as well as the layering within those deposits.

BASIN HISTORIES

Central Appalachian Basin. The Appalachian basin (Figures 1,5) is an elongate foreland basin that extends across much of the eastern United States. A foreland basin is formed on the continental side of an orogenic (mountain) belt. Pennsylvanian rocks of the central part of the Appalachian basin show a transition from marine carbonate shelf deposits into marine and nonmarine shales, siltstones, sandstones, coals, and conglomerates derived from the Appalachian Mountains. The eastern portion of the basin (the foredeep) is the thickest part of the basin, due largely to the high rate of basin subsidence. Westward, sedimentary packages of the platform and shelf are thinner (see Stevenson, 1903; Branson, 1962; Arkle, Jr. et al., 1979; Collins, 1979; Edmunds et al., 1979; Ferm, 1979; Milici and de Witt Jr., 1988; Bally, 1989).

The Pennsylvanian succession for the central part of the Appalachian basin consists of four major stratigraphic intervals that seem to represent sequence boundaries. The current classification of these strata (Hull, 1990) is essentially the classification proposed by Stevenson (1903). In ascending order this succession consists of the Pottsville Group of the Morrowan and Atokan Stages, the Allegheny Group of the Desmoinesian Stage, the Conemaugh Group of the Missourian Stage, and the Monongahela Group of the Virgilian Stage (Figure 2).

Sturgeon and others (1958) divided the Upper Pennsylvanian of eastern Ohio into named cyclothems. Because the characteristic pattern of cyclothems differs stratigraphically and geographically throughout the Pennsylvanian, identification and interbasin correlation of these units is difficult (Branson, 1962). Cyclothem-bearing stratigraphic packages (cyclothems) were modeled using SEDPAK at a scale that included such packages as individual sedimentary units, but modeling the larger depositional sequences was the objective of this work as the outcrop scale does not equal SEDPAK's basin wide scale.

A typical Appalachian-type cyclothem (Figure 3A) resulted from thrust loading during plate collisions, with minor influence from glacio-eustatic processes (which have an inferred origin in Milankovitch orbital parameters). These factors caused a wide and shallow flexural subsidence in the foreland basin. Each thrust event led to deepening and the development of a transgressive cyclothem facies in the foreland basin, whereas increased erosion rates and relative basin stability led to the development of regressive cyclothem facies. Some local variation in lithofacies are attributed to tide- and wave-dominated deltaic deposits (Ferm, 1979; Heckel, 1985; Klein and Willard, 1989).

Illinois Basin. The Illinois basin (Figures 1,6) is a roughly circular cratonic basin that covers most of Illinois and extends into adjacent areas of Indiana and Kentucky. Cratonic basins are topographically depressed regions of continental interiors. Marine transgressions flood the continent and occupy the depressed regions, sediments accumulate, and the interior of the basin subsides (Wanless, 1931, 1962, 1975, 1979; Wanless and Shepard, 1936; Wanless and Weller, 1932; Sloss, 1979; Bally, 1989).

The Pennsylvanian of the Illinois basin consists of three major subdivisions. The nomenclature (Figure 2) used for these subdivisions in Indiana and Illinois is different. In ascending order, the major stratigraphic units are McCormick Group (Illinois) and Raccoon Creek Group (Indiana) of the Morrowan and Atokan Stages; Kewanee Group (Illinois) and Carbondale Group (Indiana) of the Desmoinesian Stage; McLeansbobo Group (Illinois and Indiana) of the Missourian and Virgilian Stages (Figure 2). The single most important source of information concerning the Pennsylvanian succession is the collection of coal, oil, or water sample data at the Illinois State Geological Survey because outcrops in the Illinois basin are limited (Wanless and Shepard, 1936; Wanless and Weller, 1932; Wanless, 1931, 1962, 1975, 1979; Atherton and Palmer, 1979; Gray, 1979).

Pennsylvanian rocks of the Illinois basin were deposited in a slowly subsiding, roughly circular, depression bounded on the east by the Cincinnati Arch and on the southwest by the Ozark uplift. Streams, derived from an easterly source (perhaps the Appalachian region), deposited large quantities of sandstone and shale during the early Pennsylvanian. Middle Pennsylvanian deposition marked a transition from deltaic processes to more uniform regional cycles that extended for hundreds of kilometers (Wanless, 1931, 1962, 1975, 1979; Collinson et al., 1988). During that time, deposition of the thickest Pennsylvanian-age marine limestones of Illinois occurred. Wanless (1975) and Rice and Kehn (1979) correlated the limestones with thicker limestones of the Forest City basin and limestones of the northern Appalachian basin and thus provided some of the stratigraphic constraints for the correlation chart given in Figure 2. No record is available of rock deposited in the latest Pennsylvanian; it is estimated that more than 400 m of rock may have been removed by post-Pennsylvanian erosion (Atherton and Palmer, 1979).

A typical-Illinois cyclothem (Figure 3B) evolved through a series of tectonic subsidence phases (similar to those express in an Appalachian-type cyclothem; Figure 3A), but preserved much of the cyclicity representative of the glacio-eustatic-dominated cyclothems of Kansas-type cyclothems (Figure 3C). The Illinois-type cyclothem thus represents a step between the Appalachian and Kansas-type end member cyclothems. Differences between Illinois-type cyclothems and end member types seem to be primarily related to distance of sediment transport, the magnitude of flexural intensity and changing plate stress, rates of deposition, and relative influence from glacio-eustatic processes (Klein and Willard, 1989; Klein and Kupperman, 1992).

Forest City Basin. The Forest City basin (Figures 1,7) covers much of eastern Kansas, western Missouri, and areas of adjacent states. The Forest City basin is bounded by the Bourbon Arch to the south and the Nemaha anticline to the west (Ebanks et al., 1979).

Rocks of Morrowan and Atokan ages are found primarily in southwestern Kansas and are present in the Forest City basin in incomplete sections. The remaining succession for the Forest City basin consists of the following major subdivisions. In ascending order they are the Cherokee and Marmaton Groups of the Desmoinesian Stage; Pleasanton, Kansas City, and Lansing Groups of the Missourian Stage; and Douglas, Shawnee, and Wabaunsee Groups of the Virgilian Stage (Figure 2) (Moore et al., 1951; Branson, 1962; Ebanks et al., 1979; Heckel et al., 1979; Thompson, 1979; Bunker et al., 1988).

A typical Kansas-type cyclothem (Figure 3C) accumulates on a relatively stable platform. These cyclothems are mainly influenced by eustatic sea-level change characterized by a periodicity comparable to Milankovitch orbital parameters. The driving mechanism for these eustatic changes was continent-wide glaciations (glacio-eustatic processes) in the Southern Hemisphere from 330 to 240 Ma (Watney et al., 1989; Heckel, 1985, 1986; Klein and Willard, 1989; Bunker et al, 1988; Klein and Kupperman, 1992). Thus the Kansas-type cyclothems are preserved as marine to nonmarine transgressive-regressive sequences (Ross and Ross, 1987).

RESULTS AND INTERPRETATIONS

Sedimentary histories of an Appalachian-type foreland basin, an Illinois-type cratonic basin, and a Kansas-type platform basin were modeled using SEDPAK version 3.2 (Figures 15-17). One unifying sea level pattern (Figure 11) was used, and differences between the basins were modeled by adjusting basin subsidence and sediment accumulations rates within defined parameters obtained from decem2. The eustatic sea level curve was superimposed on Milankovitch curve of increasing amplitude (Figures 12-14), from east to west, in an attempt to reconstruct the increasing effects of glacio-eustatic processes in that direction.

Because only two to three stratigraphic locations, per basin, were used (Figures 1, 5-7), it was not the objective of this thesis to produce an exact model of each basin, but to model the overall general characteristics of each basin (Figures 8-10). Such characteristics included cyclicity, stratigraphic thicknesses, lithologies, and proportions of sand to shale to carbonate. The results, when compared to actual stratigraphic thickness measurements (Figures 5-7) and stratigraphic patterns (Table 4) from each basin (Stevenson, 1903; Moore et al., 1951, Wanless, 1962; Ebanks et al., 1979; Ferm, 1979; Gray, 1979), were astonishingly good down to the scale of individual transgressive-regressive sediment packages. Patterns of onlap, toplap, and bottom lap are in general agreement with published representations from the Pennsylvanian of the Forest City basin (see Watney et al., 1989); specific basin wide patterns of these features have not been published for the Pennsylvanian of the Appalachian or Illinois basins.

The cyclicity of sediment deposition, the rock lithologies, and proportions of shale to sand to carbonate generally match well with the actual rock record in all three basins except for minor problems, discussed below, in the Missourian and Morrowan/Atokan stages. Based on stratigraphic modeling using a single sea level curve, and by keeping subsidence rates within minimum and maximum parameters, I hypothesize that the inferred time duration (estimated from Harland et al., 1982) for the Missourian Stage is too short, and that the time duration for the Morrowan/Atokan Stages too long, discussed below.

The stratigraphic thickness modeled for the Missourian Stage, in all three basins, was only about half the actual thickness found in the rock record. This could be a result of either insufficient sedimentary input into the basin or an underestimation of the time (3 my) during which Missourian sediments accumulated. By increasing the rate of sediment being deposited and increasing the rate of basin subsidence to allow space for the additional sediment, the basin subsidence rate had to be increased above the maximum allowable value calculated by decem2 (Tables 1-3).

The stratigraphic thickness modeled for the Morrowan/Atokan Stages in the Appalachian and Illinois basins was up to twice that of the actual thickness found in the rock record. This could be a result of either too much sediment input into the basin or an overestimation of the time (19 my) during which Morrowan/Atokan sediments accumulated. By decreasing the rate of sediment being deposited, the basin subsidence rate had to be decreased to almost zero and fell below the minimum allowable value calculated by decem2 (Table 1-2). To compensate for the excess sediment, a forced erosional surface was programmed. Even though such massive erosional events are possible, there is little evidence to support the interpretation that such an event occurred in the manner that I have modeled. Morrowan/Atokan rocks are not present in the area of the Forest City basin that I modeled.

One further, important conclusion drawn from modeling sedimentary patterns in the Pennsylvanian of the Appalachian, Illinois, and Forest City basins concerns the magnitude of sea level change. According to my calculations, the maximum amount of sea level change needed for the development of Pennsylvanian cyclothems is 120 m (Figures 12-14), which is about half that estimated by some leading workers (e.g., Heckel, 1977, 1986).

CONCLUSIONS

Computer simulations of an Appalachian-type foreland basin, an Illinois-type cratonic basin, and a Forest City-type platform basin were generated in an effort to determine whether a unifying sea level pattern across ancestral North America could reproduce the stratigraphy of three different, but coeval basins. Minimum sea level changes of 120 m were needed to produce dramatic transgressive-regressive sedimentary packages that seem to mimic Pennsylvanian-age cyclothems.

The cyclicity of sediment deposition, the rock lithologies, and proportions of shale to sand to carbonate generally match well with the actual rock record in all three basins. The stratigraphic thickness in each of the basin models for the Missourian stage, however, is consistently less than that of the actual rock record, and the thickness for the Morrowan/Atokan stages is consistently more than that of the actual rock record. I hypothesize that this is due to overestimation of the time during which Morrowan/Atokan sediments accumulated and an underestimation of time during which Missourian sediments accumulated.

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REFERENCES

Arkle, T. Jr., D. R. Beissell, R. E. Larese, E. B. Nuhfer, D. G. Patchen, R. A Smosna, W. H. Gillespie, R. Lund, W. Norton, and H. W. Pfefferkorn, 1979. Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-West Virginia and Maryland, p. D1-D35. U. S. Geological Survey Professional Paper, 1110-D, Washington.

Atherton, E. and J. E. Palmer, 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Illinois, p. L1-L42. Geological Survey Professional Paper, 1110-L, Washington.

Bally, A. W., 1989. Phanerozoic basins of North America, p. 397-446. In A. W. Bally and A. R. Palmer (eds.), The Geology of North America; An Overview, Volume A, Boulder, Colorado.

Branson, C. C., 1962. Pennsylvanian System of Central Appalachians, p. 97-116. In C. C. Branson (ed.), Pennsylvanian System in the United States, Tulsa, Oklahoma.

Bunker, B. J., B. J. Witzke, W. L Watney, G. A. Ludvigson, 1988. Phanerozoic history of the central midcontinent, United States p. 243-260. In L. L. Sloss (ed.), Sedimentary Cover-North American Craton: U.S.; The Geology of North America, Volume D-2, Boulder, Colorado.

Cannon, R. and C. Kendall, 1994. SEDPAK Version 3.2 Manual, 143 P, University of South Carolina.

Collins, H. R., 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Ohio, p. E1-E26. U. S. Geological Survey Professional Paper, 1110-E.

Collinson, C., M. L. Sargent, and J. R. Jennings, 1988. Illinois Basin region p. 383-426. In L. L. Sloss (ed.), Sedimentary Cover-North American Craton: U.S.; The Geology of North America, Volume D-2, Boulder, Colorado.

Ebanks, W. J., Jr., L. L. Brady, P. H. Heckel, H. G. O'Connor, G. A. Sanderson, R. R. West, and F. W. Wilson, 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Kansas, p. Q1-Q30. U. S. Geological Survey Professional Paper, 1110-Q, Washington.

Edmunds, W. E., T. M. Berg, W. D. Sevon, R. C Pitorowski L. Heyman, and L. W. Rickard, 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Pennsylvanian and New York, p. B1-B33. Geological Survey Professional Paper, 1110-B, Washington.

Ferm, J. C., 1979. Introduction to collected papers and guidebook, p. 1-10. In J. C. Ferm and J. C. Horne (eds.), Carboniferous Depositional Environments in the Appalachian Region, University of South Carolina.

Grabau, A. W., 1940. The Rhythm of the Ages: Earth History in the Light of the Pulsation and Polar Control Theories. Popular Island Press, Peking, 561 P.

Gray, H. H., 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Indiana, p. K1-K20. U. S. Geological Survey Professional Paper, 1110-K.

Harland, W. B., A. V. Cox, P. G. Llewellyn, C. A. G. Pickton, A. G. Smith, and R. Walters, 1982. A geologic time scale. Cambridge University Press, Great Britain, 131 P.

Heckel, P.H. 1977. Origin of phosphatic black shale facies in Pennsylvanian cyclothems of mid-continent North America. American Association of Petroleum Geologists Bulletin, 61:1045-1068.

Heckel, P. H., L. L. Brady, W. J. Ebanks, Jr., and R. K. Pabian, 1979. Field guide to Pennsylvanian cyclic deposits in Kansas and Nebraska. Kansas Geological Survey Guidebook Series, 4, 79 P.

Heckel, P. H., 1979. Changing concepts of midcontinent Pennsylvanian cyclothems, North America. Proceedings of the IX International Carboniferous Congress, p. 535-553.

Heckel, P. H., 1985. Current view of midcontinent Pennsylvanian cyclothems, p. 1-22. In W. L. Watney, R. L Kaesler, and K. D. Newell (eds.), Recent Interpretations of Late Paleozoic Cyclothems. Society of Economic Paleontologists, Mid-Continent Section, Third Annual Meeting and Field Conference, Proceedings (Lawrence).

Heckel, P. H., 1986. Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive deposition cycles along midcontinent outcrop belt, North America. Geology, 14:779-794.

Hull, D. N., 1990. Generalized column of bedrock units in Ohio. Ohio Department of Natural Resources, 1 P.

Kendall, C. G. St. C., and I. Lerche, 1989. The rise and fall of eustasy. Society of Economic Paleontologists and Mineralogists Special Publications, 42:3-17.

Kendall, C. G. St. C., P. Moore, J. Strobel, R. Cannon, J. Bezdek, and G. Biswas, 1989. Simulation of the sedimentary fill of basins. Kansas Geological Survey Subsurface Geology Series, 12:1-4.

Kendall, C. G. St. C., P. Moore, J. Strobel, R. Cannon, M. Perlmutter, J. Bezdek, and G. Biswas, 1991. Simulation of the sedimentary fill of basins. Kansas Geological Survey Bulletin, 233:9-30.

Klein G. dev., and J. B. Kupperman, 1992. Pennsylvanian cyclothems: methods of distinguishing tectonically induced changes in sea level from climatically induced changes. Geological Society of America Bulletin, 104:166-175.

Klein, G. dev., D. A. Willard, 1989. Origin of the Pennsylvanian coal-bearing cyclothems of North America. Geology, 17:152-155.

Kominz, M. A., and G. C. Bond, 1986. Geophysical modelling of the thermal history of foreland basins. Nature, 320:252-256.

Milici, R. C., and W. de Witt, Jr., 1988. The Appalachian Basin p. 427-469. In L. L. Sloss (ed.), Sedimentary Cover-North American Craton: U.S.; The Geology of North America, Volume D-2, Boulder, Colorado.

Moore, R. C., 1931. Pennsylvanian cycles in the northern midcontinent region. Illinois Geological Survey Bulletin, 60:247-257.

Moore, R. C., J. C. Frey, J. M. Jewett, W. Lee, and H. G. O'Connor, 1951. The Kansas rock column. Geological Survey of Kansas Bulletin, 89, 132 P.

Rice, C. L., and T. M. Kehn, 1979. Stratigraphic relations of Pennsylvanian rocks of the Eastern Interior (Illinois) and Appalachian basins in Kentucky. Part II, F. R. Ettensohn and G. R. Dever, Jr. (eds.), In Carboniferous Geology from the Appalachian Basin to the Illinois Basin through Eastern Ohio and Kentucky, University of Kentucky.

Ross, C. A., and J. R. P Ross, 1987. Late Paleozoic sea levels and depositional sequences. Cushman Foundation for Foraminiferal Research Special Publication, 24:137-149.

Ross, W. C., 1991. Cyclic stratigraphy, sequence stratigraphy, and stratigraphic modeling from 1964 to 1989; twenty-five years of progress? Kansas Geological Survey Bulletin, 233:4-8.

Sloss, L. L., 1979. Plate-tectonic implications of the Pennsylvanian System in the Illinois Basin, p. 107-112. In J. E. Palmer and R. R. Dutcher (eds.), Depositional and Structural History of the Pennsylvanian System of the Illinois Basin, Part 2: Invited papers, Urbana, Illinois.

Stevenson, J. J., 1903. Lower Carboniferous of the Appalachian Basin. The Geological Society of America Bulletin, 14:15-96.

Sturgeon, M. T., and others, 1958. The geology and mineral resources of Athens County, Ohio: Ohio Geological Survey Bulletin, 57, 600 P.

Thompson, T. L., 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Missouri, p. N1-N22. U. S. Geological Survey Professional Paper, 1110-N, Washington.

Vail, P. R., et al, 1977. Seismic stratigraphy and global changes of sea level (parts 1-11), p. 49-212. In C. E. Payton (ed.), Seismic Stratigraphy--Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists, Memoir 26.

Vail, P. R., 1992. The evolution of seismic stratigraphy and the global sea-level curve, p. 83-91. In R. H. Dott, Jr. (ed.), Eustasy: The Historical Ups and Downs of a Major Geological Concept. Geological Society of America Memoir, 180.

Van Wagoner, J. C., R. M. Mitchum, Jr., H. W. Posamentier, and P. R. Vail, 1987. Seismic stratigraphy interpretation using sequence stratigraphy. Part 2: Key definitions of sequence stratigraphy, p. 11-14. In A. W. Bally (ed.), Atlas of Seismic Stratigraphy, Volume 1. American Association of Petroleum Geologists Studies in Geology, 27.

Van Wagoner, J. C., H. W. Posamentier R. M. Mitchum, P. R. Vail, J. F. Sarg, T. S. Loutit, and J. Hardenbol, 1988. An overview of sequence stratigraphy and key definitions. Society of Economic Paleontologists and Mineralogists Special Paper, 42:39-45.

Wanless, H. R., 1931. Pennsylvanian cycles in western Illinois. Illinois State Geological Survey Bulletin, 60:179-193.

Wanless, H. R., 1962. Pennsylvanian rocks of Eastern Interior basin, p. 4-59. In C. C. Branson (ed.), Pennsylvanian System in the United States.

Wanless, H. R., 1975. Illinois basin region, p 71-95. In E. D. McKee, and E. J. Crosby (eds.), Paleotectonic Investigations of the Pennsylvanian System in the United States; Part 1, Introduction and Regional Analysis of the Pennsylvanian System. U.S. Geological Survey Professional Paper 853-E.

Wanless, H. R., 1979. Depositional history of the Pennsylvanian System in the Illinois basin - a summary of work, p. 21-27. In J. E. Palmer and R. R. Dutcher (eds.), Depositional and Structural History of the Pennsylvanian System of the Illinois Basin, Part 2: Invited papers.

Wanless, H. R., and J. M. Weller, 1932. Correlation and extent of Pennsylvanian cyclothems. Geological Society of America Bulletin, 43:1003-1016.

Wanless, H. R., and F. P. Shepard, 1936. Sea level and climatic changes related to late Paleozoic cycles. Geological Society of America Bulletin, 47:1177-1206.

Weller, J. M., 1930. Cyclical sedimentation of the Pennsylvanian Period and its significance. Journal of Geology, 38:97-135.

Weller, J. M., 1964. Development of the concept and interpretation of cyclic sedimentation. Kansas Geological Survey Bulletin, 169:607-621.

Watney, W. L., J. French, and E. K. Franseen (eds), 1989, Sequence Stratigraphic Interpretations and Modeling of Cyclothems in the Upper Pennsylvanian (Missourian) Lansing and Kansas City Groups in Eastern Kansas. Kansas Geological Society, 41st Annual Field Trip (Lawrence).

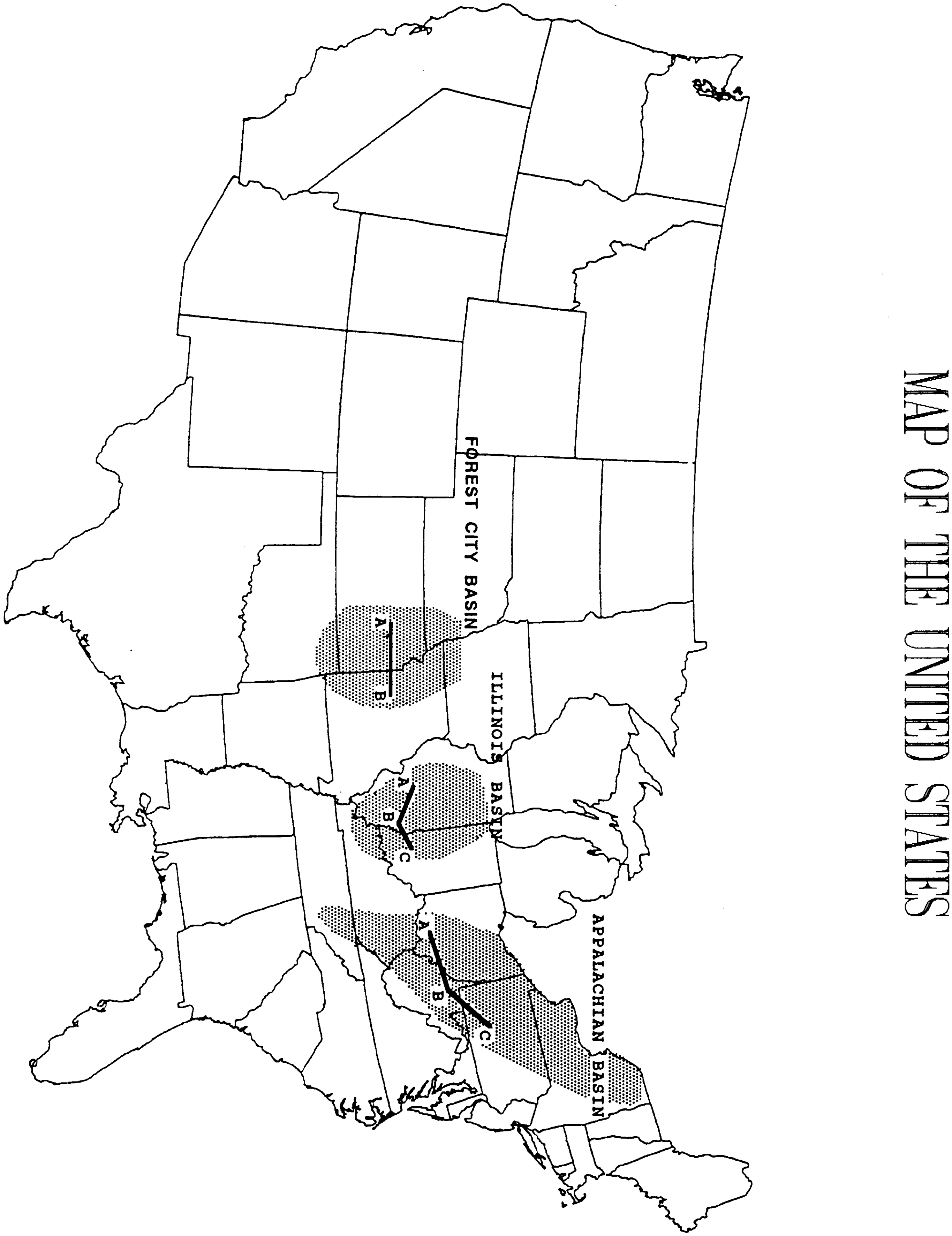


Figure 1. Geographic distribution of the Forest City basin, Illinois basin, and Appalachian basin including the east-west cross section used for the two dimensional basin model.

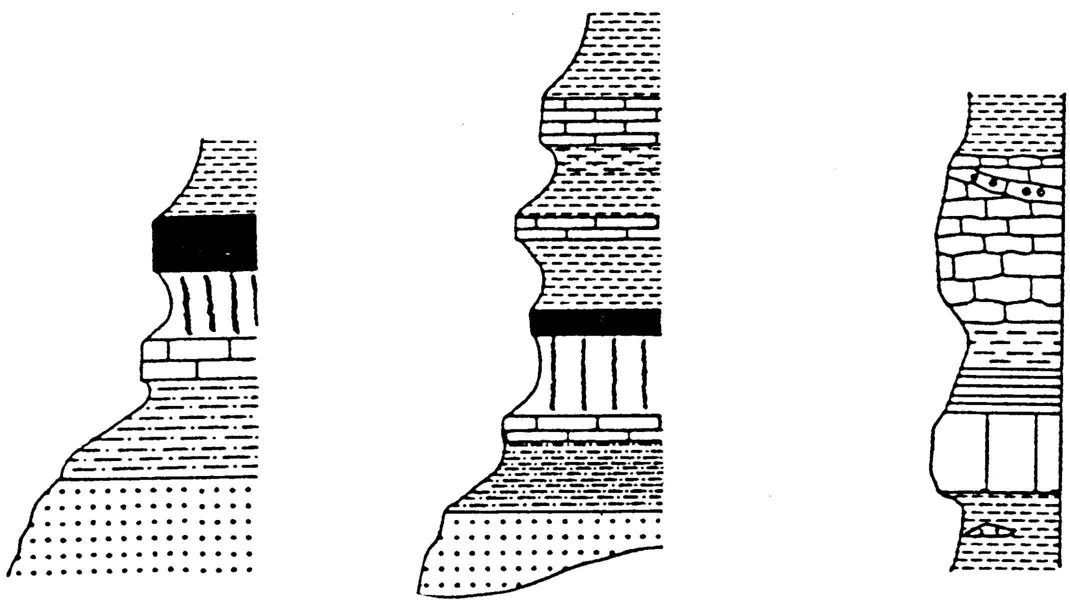
Geologic Age (Ma) (Based on Harland et al., 1982)		APPALACHIAN BASIN			ILLINOIS BASIN			FOREST CITY BASIN	
		Western Pennsylvania	Northern W. Virginia	Southern Ohio	Western Indiana	Southern Illinois	Western Illinois	Eastern Missouri	Western Kansas
286–292	VIRGILIAN	Monongahela	Monongahela	Monongahela	McLeansboro	McLeansboro	McLeansboro	Wabaunsee Shawnee Douglas	Wabaunsee Shawnee Douglas
292–295	MISSOURIAN	Conemaugh	Conemaugh	Conemaugh				Lansing Kansas City Pleasanton	Lansing Kansas City Pleasanton
295–301	DESMOINESIAN	Allegheny	Allegheny	Allegheny	Carbondale	Kewanee	Kewanee	Marmaton Cherokee	Marmaton Cherokee
301–320	MORROWAN AND ATOKAN	Pottsville	Pottsville	Pottsville	Raccoon Creek	McCormick	McCormick	undifferentiated	undifferentiated

Figure 2. Correlation chart showing principal stratigraphic groups in each of the areas of interest.

A
Appalachian-Type
Cyclothem

B
Illinois-Type
Cyclothem

C
Kansas-Type
Cyclothem



Foreland-Flexure
Dominated

Mixed Marine-Eustatic
& Foreland-Flexure
Dominated

Marine-Eustatic
Dominated

Figure 3. Examples of typical cyclothems from the A) Appalachian basin (Appalachian-type cyclothem), B) Illinois basin (Illinois-type cyclothem), and C) Forest City basin (Kansas-type cyclothem). Dash pattern = gray shale; dots = sandstone; brick pattern = limestone; black = coal; vertical wavy lines = underclay; dots and dashes = siltstone; horizontal lines = black shale. From Klein and Willard (1989).

Paleogeographic Map, 295 Ma

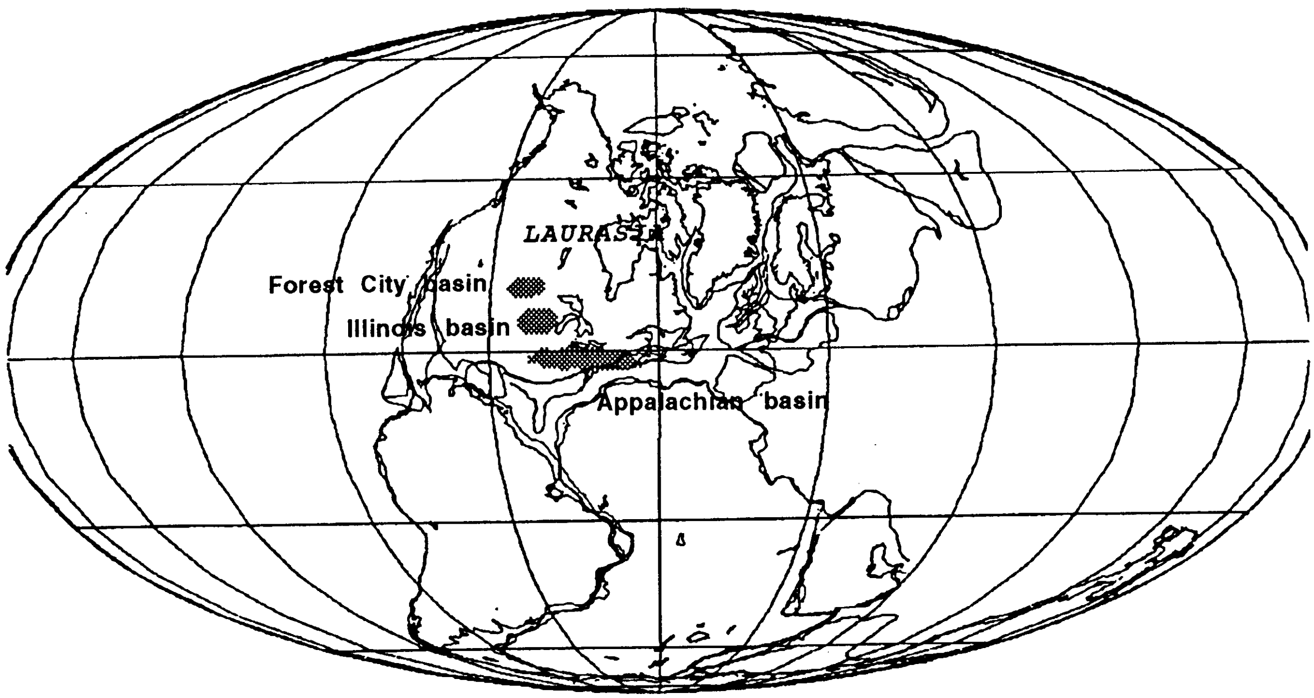


Figure 4. Paleogeographic location of the ancestral North American continent Laurasia (Laurussia), and locations of the Appalachian, Illinois, and Forest City basins during the Late Pennsylvanian (295 Ma).

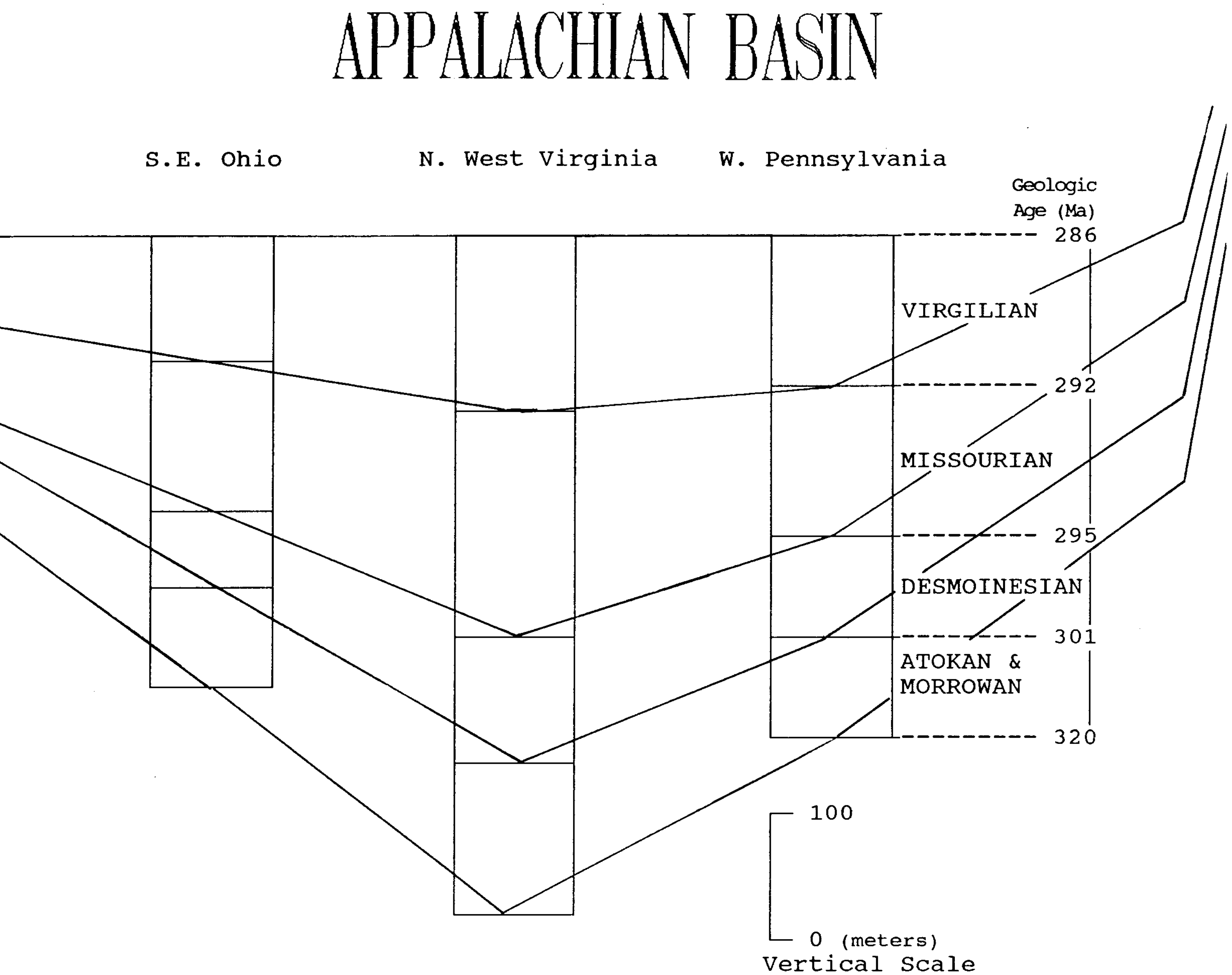


Figure 5. Generalized thicknesses of strata in three areas in the Appalachian basin. Based on information in Stevenson (1903) and Ferm (1979).

ILLINOIS BASIN

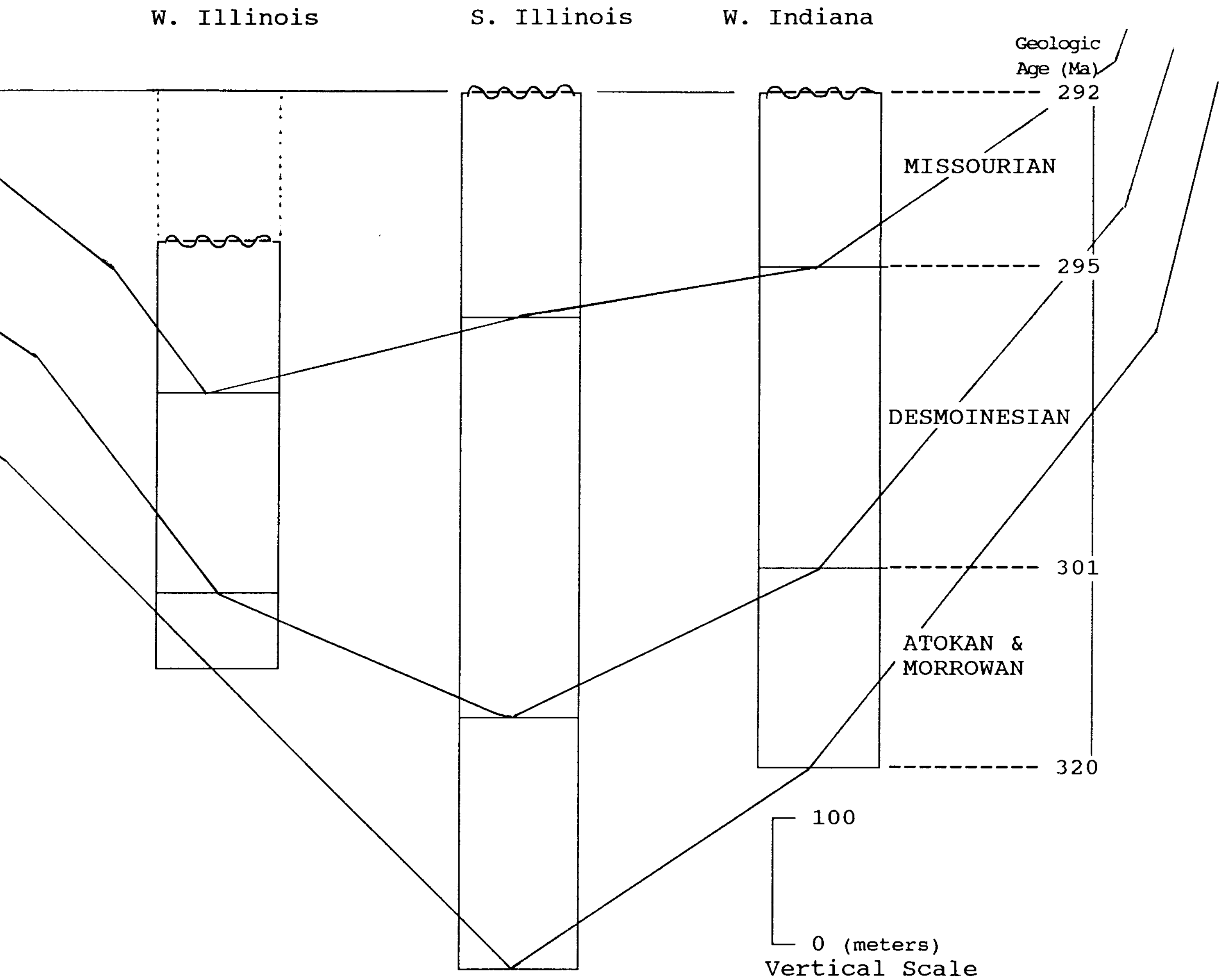


Figure 6. Generalized thicknesses of strata in three areas in the Illinois basin. Strata of the Virgilian and portions of the Missourian in western Illinois and western Indiana have been eroded. Based on information in Wanless (1962) and Gray (1979).

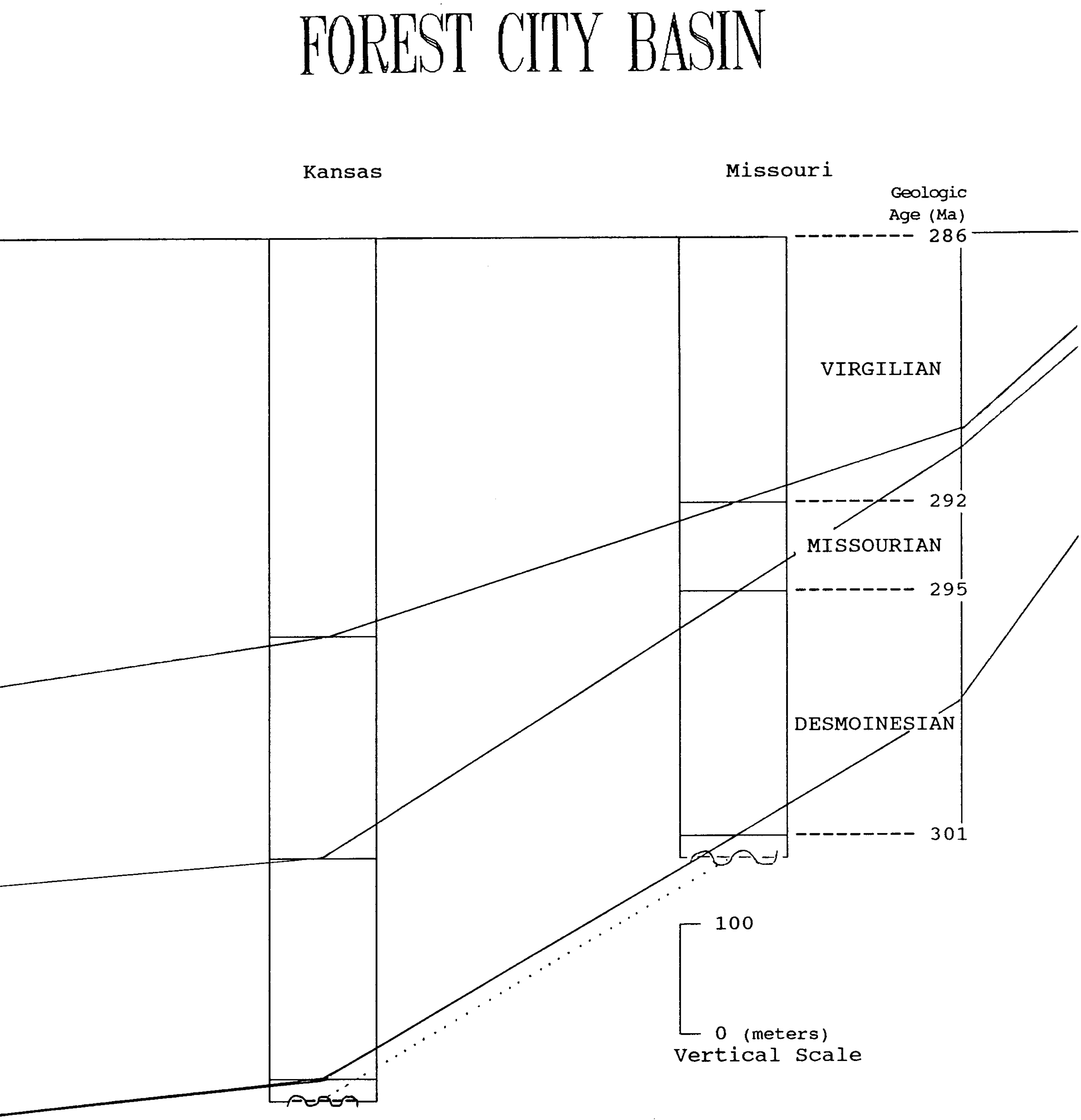


Figure 7. Generalized stratigraphic thickness of strata in two areas in the Forest City basin. The Morrowan and Atokan stages are sporadic throughout Kansas and Missouri. Based on information in Moore et al. (1951), Ebanks et al. (1979), and Thompson et al. (1979).

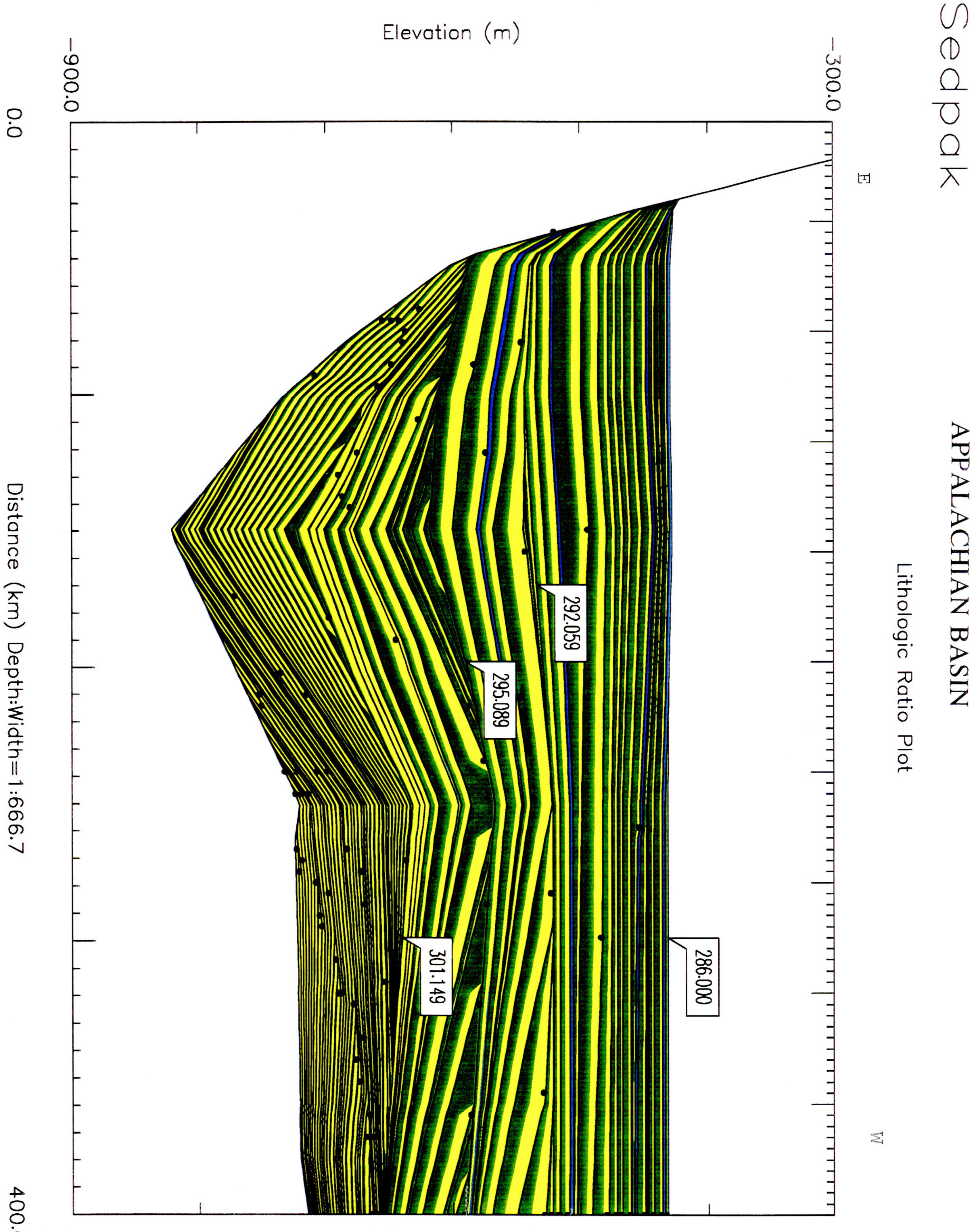


Figure 8. Reconstruction of Pennsylvanian strata in the Appalachian basin, modeled using SEDPAK.

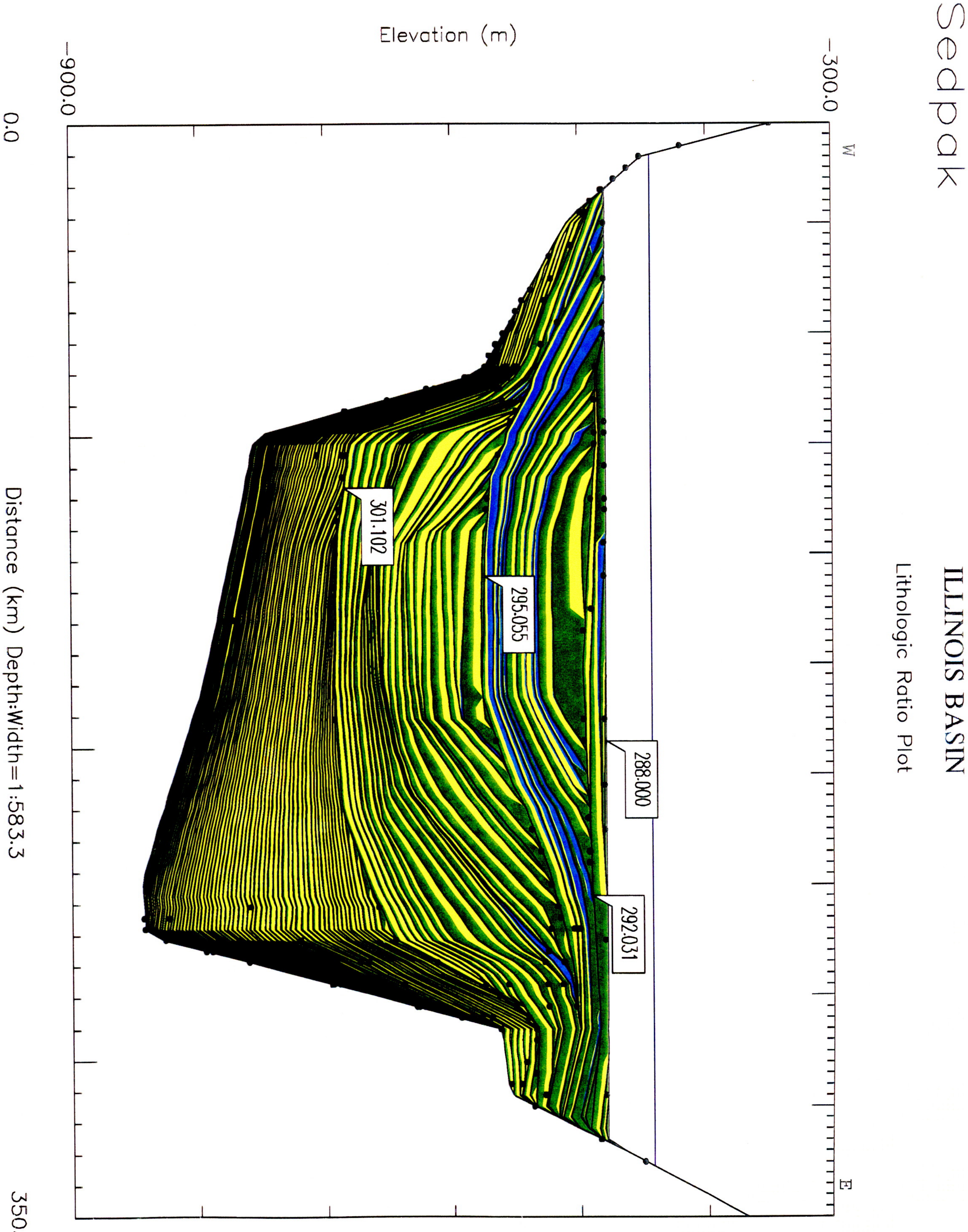


Figure 9. Reconstruction of Pennsylvanian strata in the Illinois basin, modeled using SEDPAK.

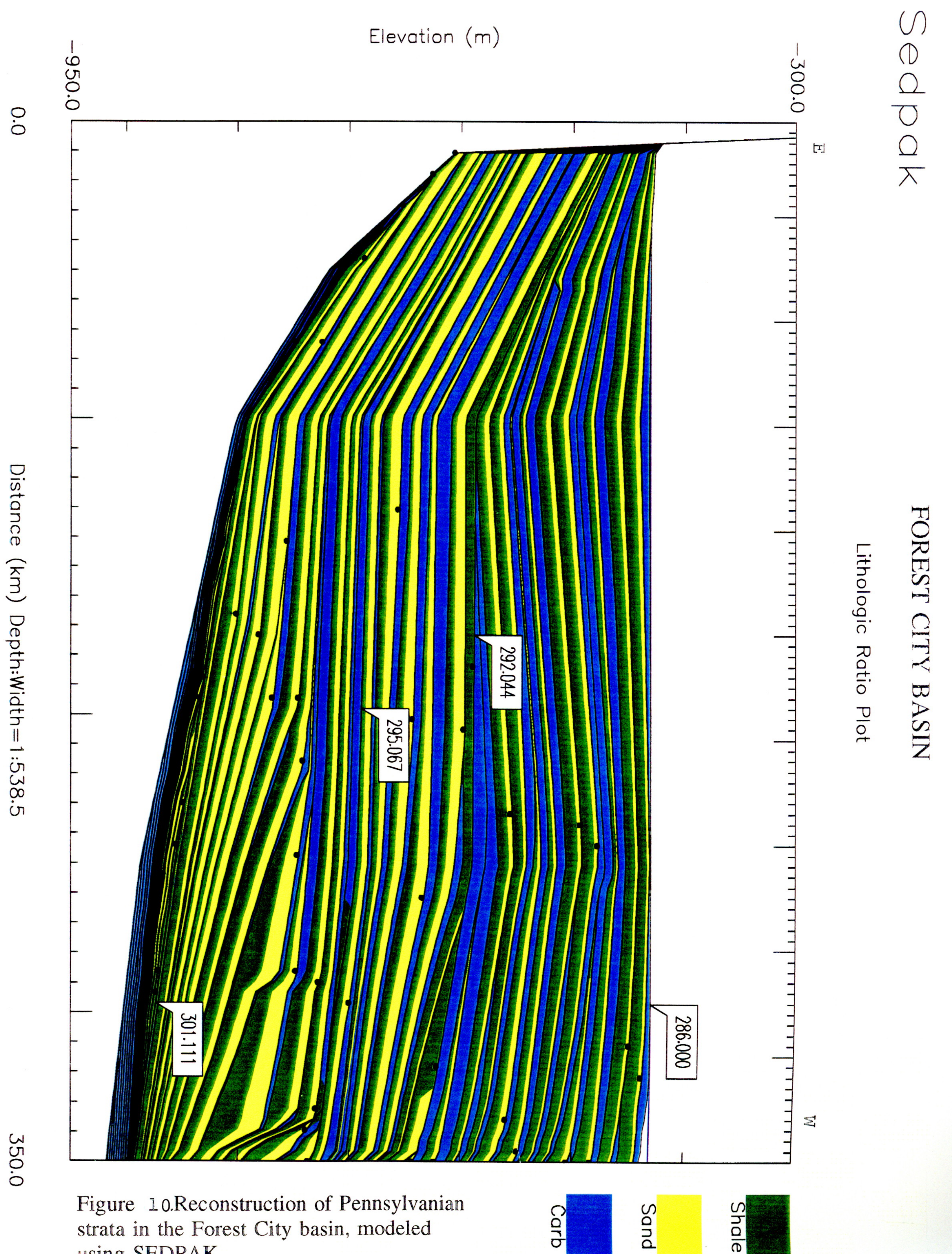


Figure 10.Reconstruction of Pennsylvanian strata in the Forest City basin, modeled using SEDPAK.

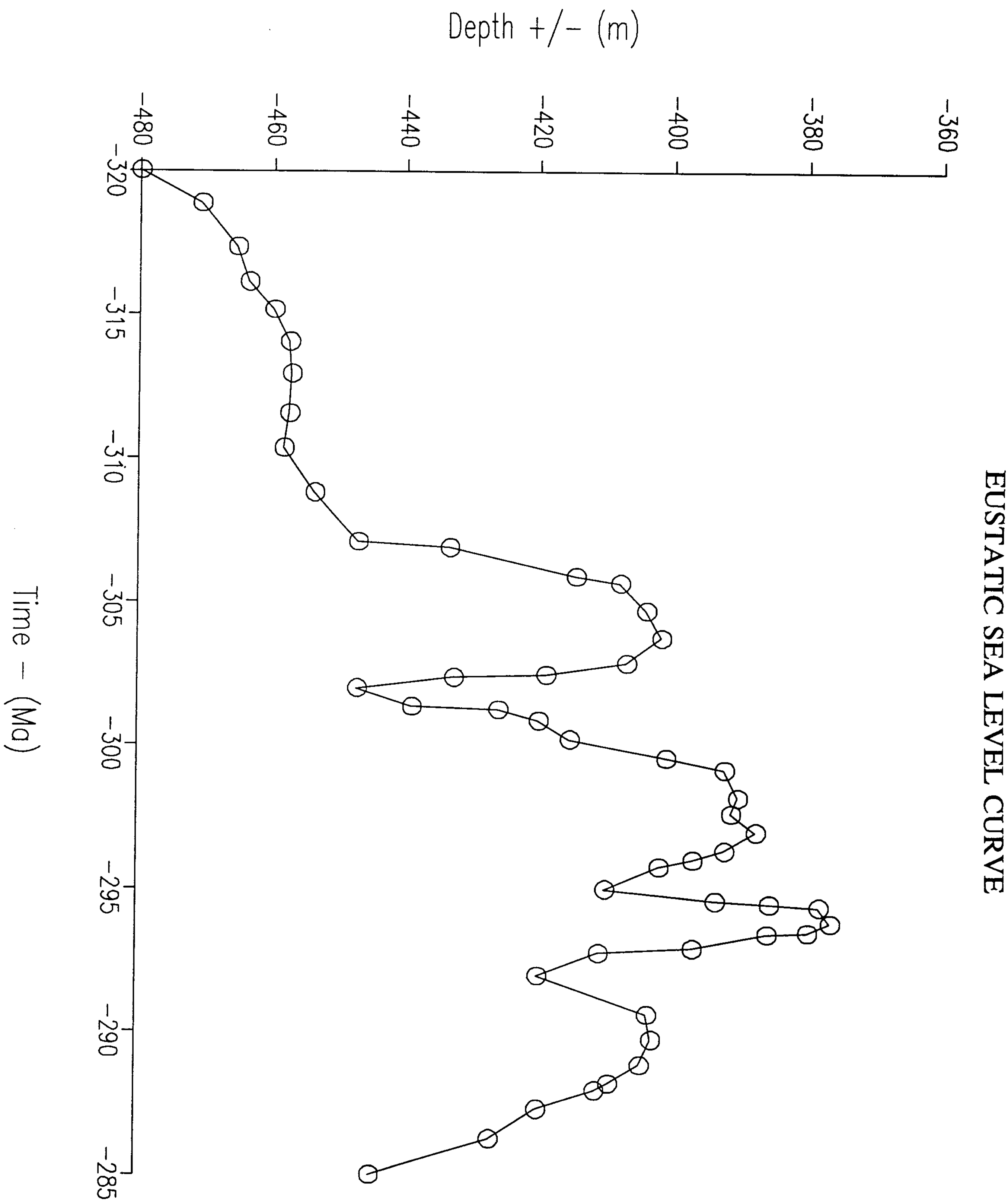


Figure 11.Eustatic curve used for all three basin models using SEDPAK, based on Ross and Ross (1987).

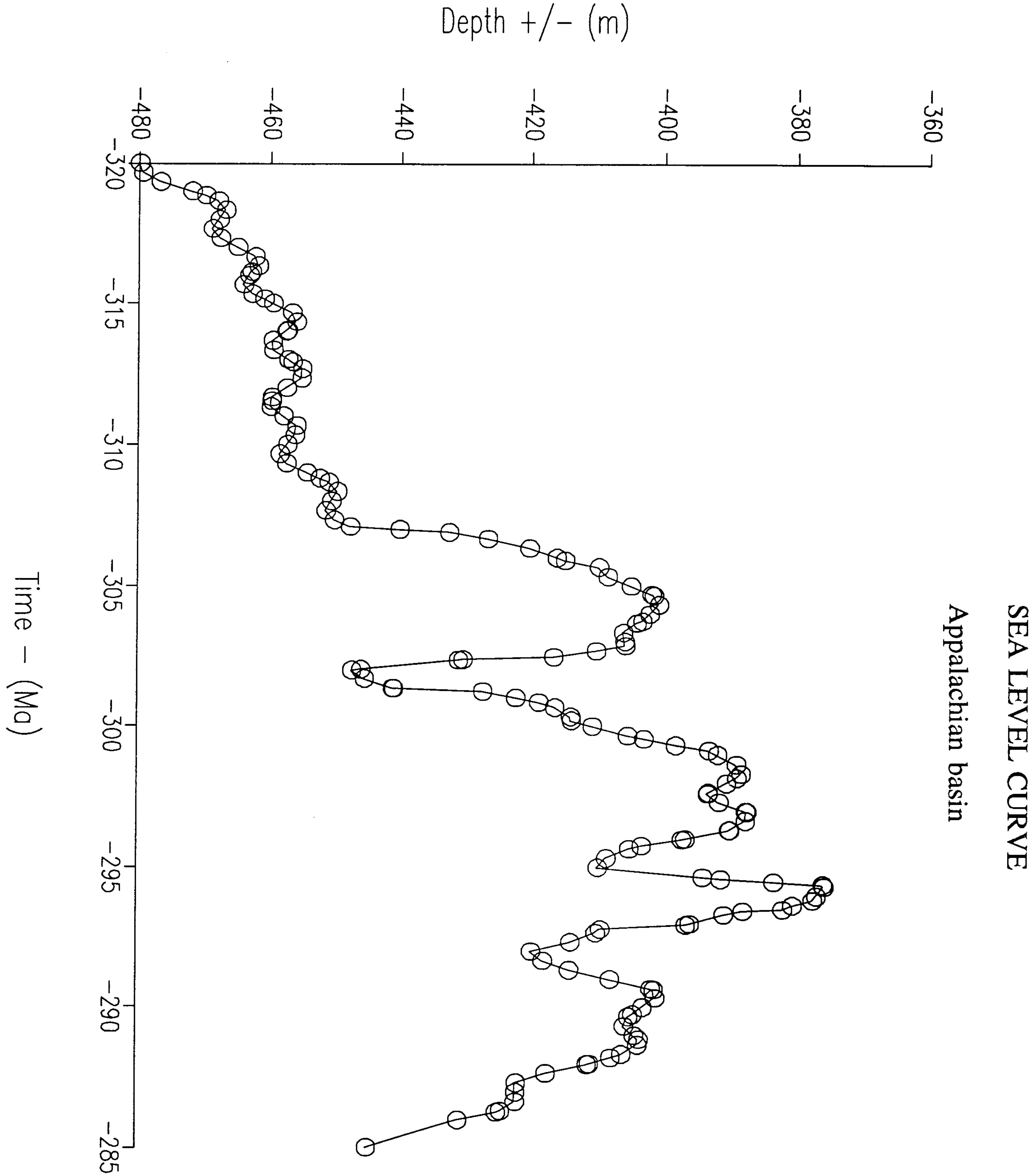


Figure 12. Sea level curve for the Appalachian basin superimposed on Milankovitch-type orbital parameters (amplitude = 2.5 meters) using SEDPAK.

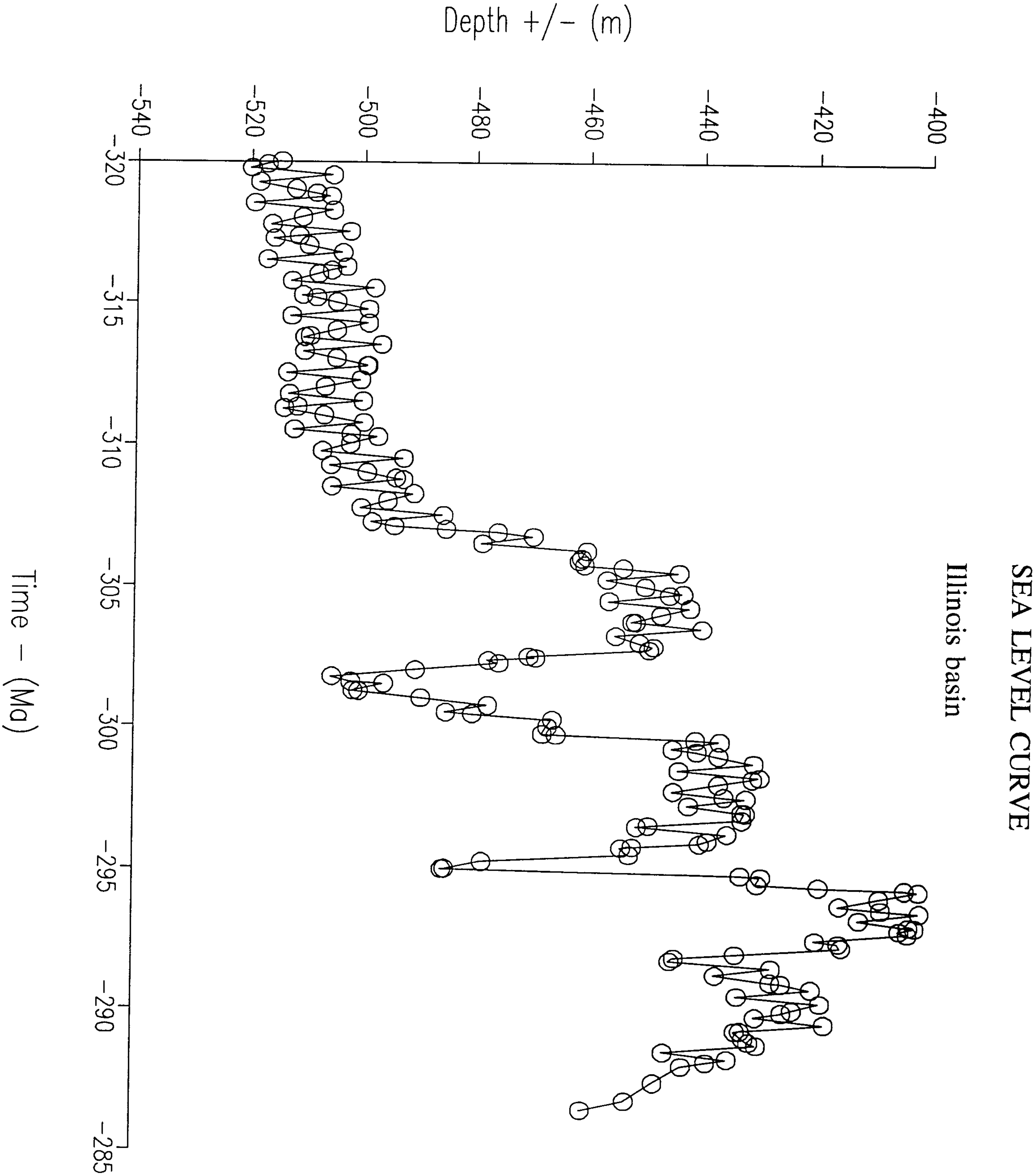


Figure 13. Sea level curve for the Illinois basin superimposed on Milankovitch-type orbital parameters (amplitude = 8 meters) using SEDPAK.

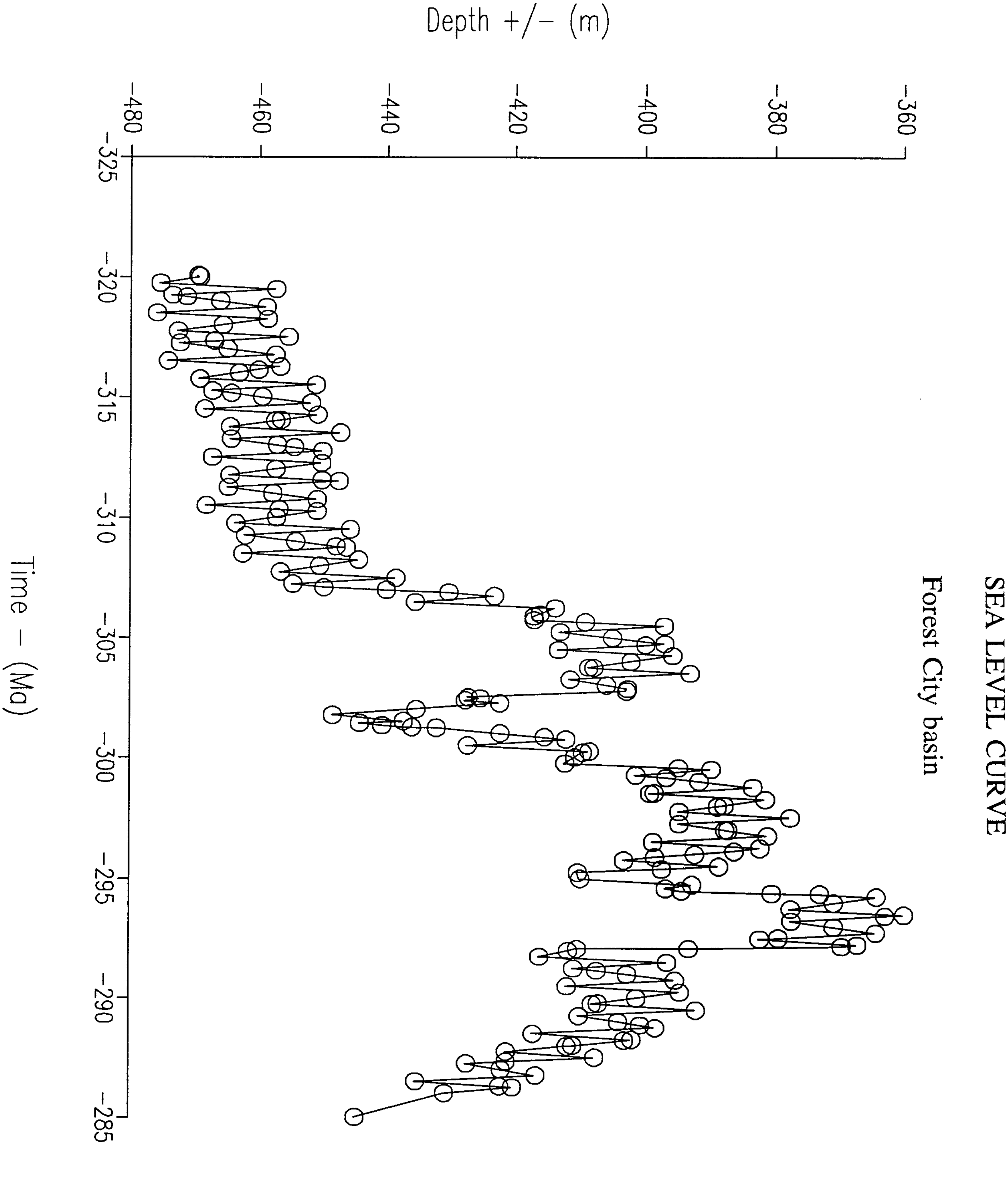


Figure 14. Sea level curve for the Forest City basin superimposed on Milankovitch-type orbital parameters (amplitude = 12 meters) using SEDPAK.

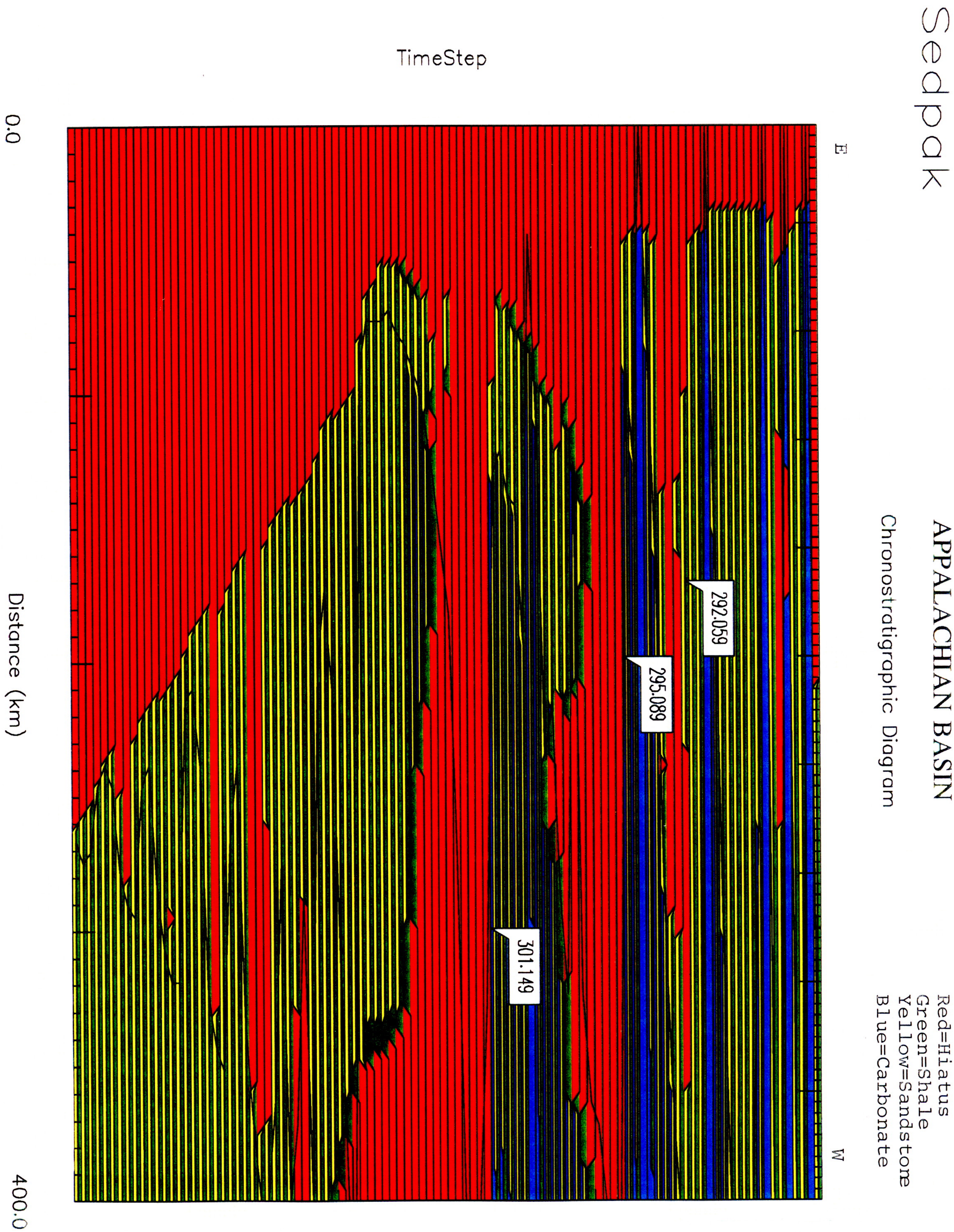


Figure 15. Chronostratigraphic diagram of the Appalachian basin, modeled using SEDPAK.

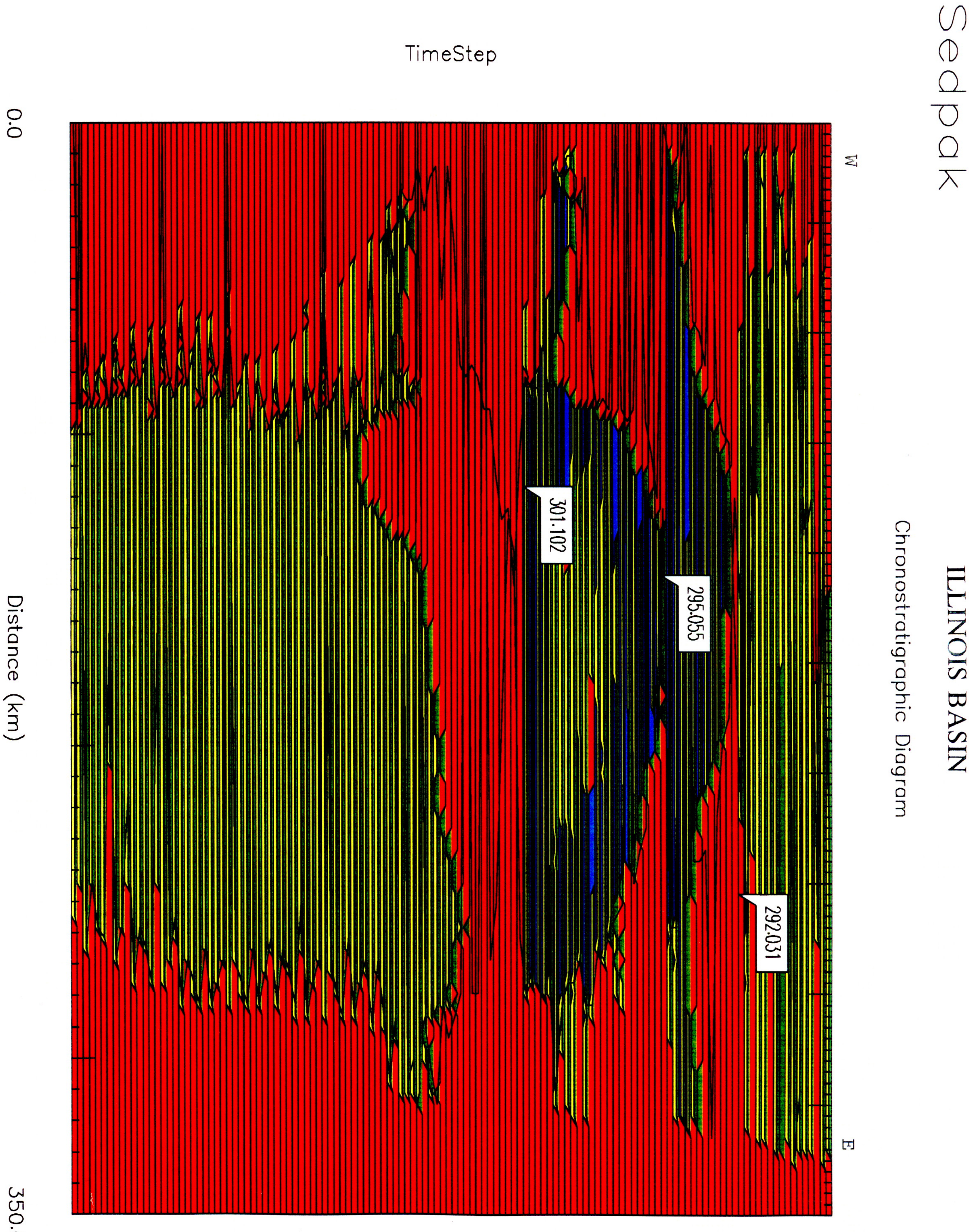


Figure 16. Chronostratigraphic diagram of the Illinois basin, modeled using SEDPAK.

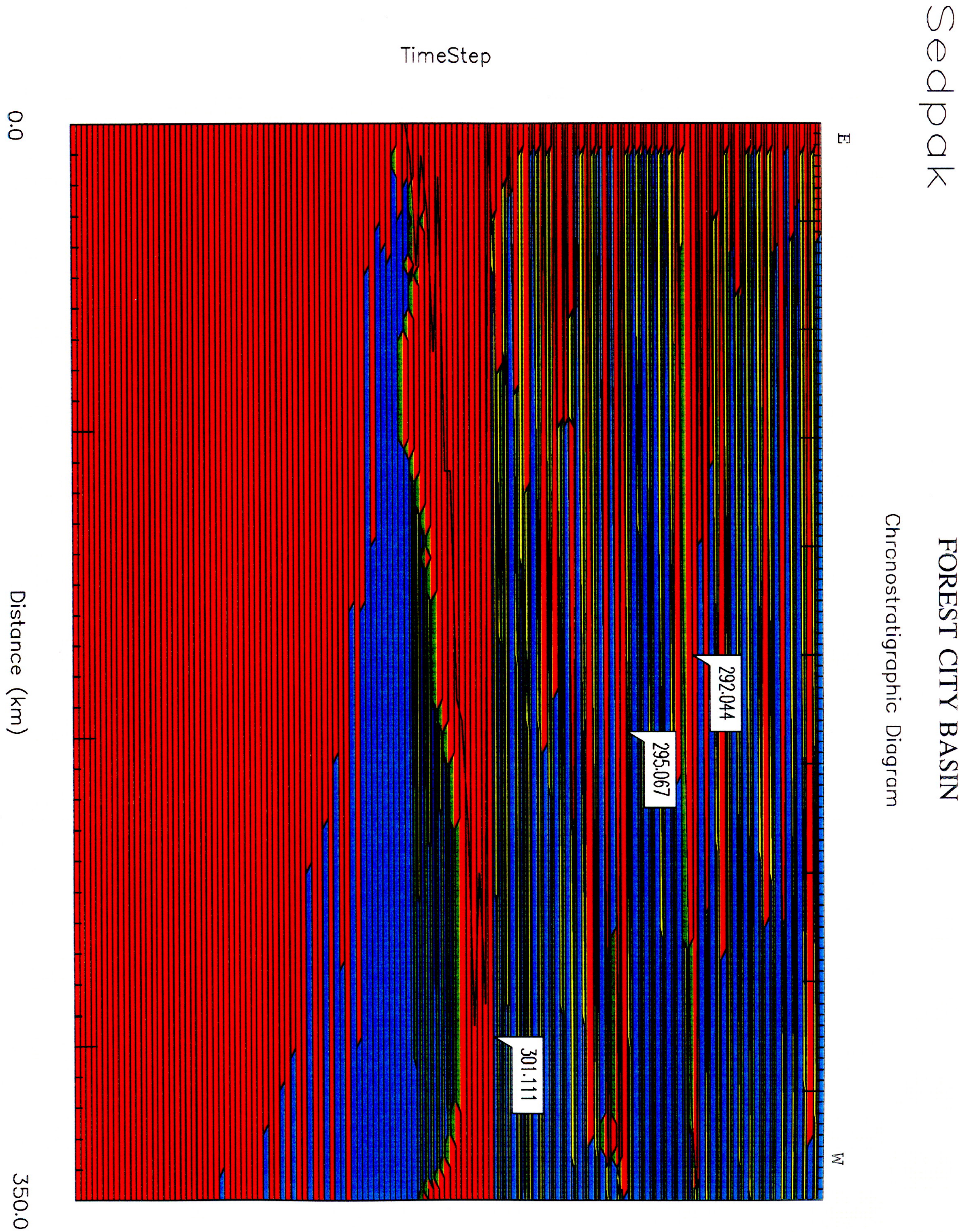


Figure 17. Chronostratigraphic diagram of the Forest City basin, modeled using SEDPAK.

PENNSYLVANIA:

Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan	96.795	152.057	75.000	152.057	0	200
desmoi	184.357	299.139	155.000	324.012	0	200
missou	271.787	468.180	265.000	543.464	0	200
virgil	320.634	596.189	375.000	726.132	0	200

Tectonic subsidence results as they correspond to minimum and maximum water depth

Section	tsubs-min	tsubs-max
atokan	96.795	296.795
desmoi	184.357	384.357
missou	271.787	471.787
virgil	320.634	520.634

WEST VIRGINIA:

Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan	145.698	227.358	110.000	227.358	0	200
desmoi	211.511	358.685	200.000	394.141	0	200
missou	349.803	624.101	370.000	727.409	0	200
virgil	435.257	814.912	510.000	999.628	0	200

Tectonic subsidence results as they correspond to minimum and maximum water depth

Section	tsubs-min	tsubs-max
atokan	145.698	345.698
desmoi	211.511	411.511
missou	349.803	549.803
virgil	435.257	635.257

OHIO:

Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan	93.135	144.749	70.000	144.749	0	200
desmoi	139.611	234.394	130.000	251.301	0	200
missou	235.477	418.289	250.000	471.491	0	200
virgil	336.951	596.036	350.000	702.485	0	200

Tectonic subsidence parameters (minimum and maximum water depth)

Section	tsubs-min	tsubs-max
atokan	93.135	293.135
desmoi	139.611	339.611
missou	235.477	435.477
virgil	336.951	536.951

t.subs-sed -subsidence of the basin in the absence of sediment
sstar -thickness of delithified sediment at time of final deposition of the entire column
obs sed -present sediment thickness
delith -sum of all maximally decompacted sediment thicknesses
wd1 and wd2 -minimum and maximum water depths, respectively
tsubs-min -minimum tectonic subsidence parameter
tsub-max -maximum tectonic subsidence parameter

Table 1. Subsidence and sedimentary thickness values for the Appalachian basin obtained from the decem2 delithification program from stratigraphic thickness and lithology information provided by Stevenson (1903) and Ferm (1979).

INDIANA:

Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan	181.714	308.221	170.000	308.221	0	200
desmoi	379.351	679.863	400.000	752.485	0	200
missou	538.419	1007.150	620.000	1199.794	0	200
virgil	642.053	1240.813	790.000	1563.101	0	200

Tectonic subsidence results as they correspond to minimum and maximum water depth

Section	tsubs-min	tsubs-max
atokan	181.714	381.714
desmoi	379.351	579.351
missou	538.419	738.419
virgil	642.053	842.053

SOUTHERN ILLINOIS:

Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan	193.849	339.414	200.000	339.414	0	200
desmoi	472.637	869.103	530.000	945.288	0	200
missou	599.326	1141.613	720.000	1343.484	0	200
virgil	658.715	1277.716	820.000	1577.696	0	200

Tectonic subsidence results as they correspond to minimum and maximum water depth

Section	tsubs-min	tsubs-max
atokan	193.849	393.849
desmoi	472.637	672.637
missou	599.326	799.326
virgil	658.715	858.715

WESTERN ILLINOIS:

Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan	71.309	114.879	60.000	114.879	0	200
desmoi	245.085	401.208	210.000	427.394	0	200
missou	405.903	706.854	400.000	824.383	0	200
virgil	490.462	882.865	520.000	1096.603	0	200

Tectonic subsidence parameters (minimum and maximum water depth)

Section	tsubs-min	tsubs-max
atokan	71.309	271.309
desmoi	245.085	445.085
missou	405.903	605.903
virgil	490.462	690.462

t.subs-sed -subsidence of the basin in the absence of sediment
sstar -thickness of delithified sediment at time of final deposition of the entire column
obs sed -present sediment thickness
delith -sum of all maximally decompacted sediment thicknesses
wd1 and wd2 -minimum and maximum water depths, respectively
tsubs-min -minimum tectonic subsidence parameter
tsub-max -maximum tectonic subsidence parameter

Table 2. Subsidence and sedimentary thickness values for the Illinois basin obtained from the decem2 delithification program from stratigraphic thickness and lithology information provided by Wanless (1962) and Gray (1979).

MISSOURI:
Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan						
desmoi	247.378	411.982	220.000	411.982	0	200
missou	300.676	524.733	300.000	573.027	0	200
virgil	475.819	880.767	540.000	1028.785	0	200

Tectonic subsidence results as they correspond to minimum and maximum water depth

Section	tsubs-min	tsubs-max
atokan		
desmoi	247.378	447.378
missou	300.676	500.676
virgil	475.819	675.819

KANSAS:
Tectonic subsidence results

Section	t.subs-sed	sstar	obs sed	delith	wd1	wd2
atokan						
desmoi	230.953	380.553	200.000	380.553	0	200
missou	361.922	660.272	400.000	740.839	0	200
virgil	600.684	1170.750	760.000	1375.403	0	200

Tectonic subsidence results as they correspond to minimum and maximum water depth

Section	tsubs-min	tsubs-max
atokan		
desmoi	230.953	430.953
missou	361.922	561.922
virgil	600.684	800.684

t.subs-sed -subsidence of the basin in the absence of sediment
sstar -thickness of delithified sediment at time of final deposition of the entire column
obs sed -present sediment thickness
delith -sum of all maximally decompacted sediment thicknesses
wd1 and wd2 -minimum and maximum water depths, respectively
tsubs-min -minimum tectonic subsidence parameter
tsub-max -maximum tectonic subsidence parameter

Table 3. Subsidence and sedimentary thickness values for the Forest City basin obtained from the decem2 delithification program from stratigraphic thckness and lithology information provided by Moore et al. (1951), Ebanks et al. (1979), and Thompson et al. (1979).

Lithologies and Proportions of Shale to Sand to Carbonates

APPALACHIAN BASIN			
	Pennsylvania	W. Virginia	Ohio
Morrowan/Atokan	50% Shale 50% Sandstone	60% Shale 40% Sandstone	52% Shale 48% Sandstone
Desmoinesian	60% Shale 40% Sandstone	40% Shale 60% Sandstone	31% Shale 66% Sandstone 3% Carbonate
Missourian	54% Shale 45% Sandstone 1% Carbonate	62% Shale 37% Sandstone 1% Carbonate	42% Shale 47% Sandstone 11% Carbonate
Virgilian	28% Shale 42% Sandstone 3% Carbonate	53% Shale 24% Sandstone 23% Carbonate	78% Shale 20% Sandstone 2% Carbonate

ILLINOIS BASIN			
	W. Indiana	S. Illinois	W. Illinois
Morrowan/Atokan	50% Shale 46% Sandstone 4% Carbonate	40% Shale 60% Sandstone	40% Shale 60% Sandstone
Desmoinesian	70% Shale 26% Sandstone 4% Carbonate	75% Shale 25% Sandstone <1% Carbonate	70% Shale 26% Sandstone 4% Carbonate
Missourian	80% Shale 10% Sandstone 10% Carbonate	80% Shale 5% Sandstone 15% Carbonate	80% Shale 5% Sandstone 15% Carbonate

FOREST CITY BASIN		
	Missouri	Kansas
Morrowan/Atokan	Undifferentiated	
Desmoinesian	61% Shale 20% Sandstone 19% Carbonate	65% Shale 20% Sandstone 15% Carbonate
Missourian	52% Shale 23% Sandstone 25% Carbonate	62% Shale 27% Sandstone 11% Carbonate
Virgilian	66% Shale 15% Sandstone 19% Carbonate	68% Shale 12% Sandstone 20% Carbonate

Table 4. Lithologies and proportions of shale to sand to carbonate in each of the three basins. Based on information in Stevenson (1903), Moore et al.(1951), Ebanks et al. (1979), Ferm (1979), Gray (1979), Thompson et al. (1979), and Wanless (1962).